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EPICENTRAL ESTIMATION FOR FIVE LASA EVENTS USING FREQUENCY-WAVENUMBER SPECTRA

Special Scientific Report No. 21

LARGE-ARRAY SIGNAL AND NOISE ANALYSIS

Prepared by

Frank H. Binder   Jerry R. Peebles

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TEXAS INSTRUMENTS INCORPORATED
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Contract No. AF 33(657)-16678

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
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SECTION I

INTRODUCTION AND SUMMARY

This report discusses the results using various f-$\vec{k}$ spectral techniques in locating five fairly weak events with magnitudes ranging from 4.4 to 4.8. Three different subarray configurations (Figure I-1) were used to process these events:

- Processed subarray outputs from A0 through the D-ring
- The extended E3 subarray
- The standard F1 subarray

To complement theoretical f-$\vec{k}$ spectral work using location statistics,[1] this experiment applied various f-$\vec{k}$ spectral techniques to some of the seismic events. There are several pertinent questions to be answered.

- Does any f-$\vec{k}$ technique give a more accurate epicentral location than the others?
- Can some f-$\vec{k}$ techniques give accurate location while requiring significantly fewer calculations than other techniques?
- How do the epicentral locations obtained from arrays of different apertures compare?

It was found that the best strategy for approximately determining the epicenter of weak events at LASA is to use bandpassed subarray outputs to form multiple beams in the time domain. The extended E3 subarray gave correct approximate epicenters for the events studied, while a standard subarray does not give satisfactory approximate epicenters.

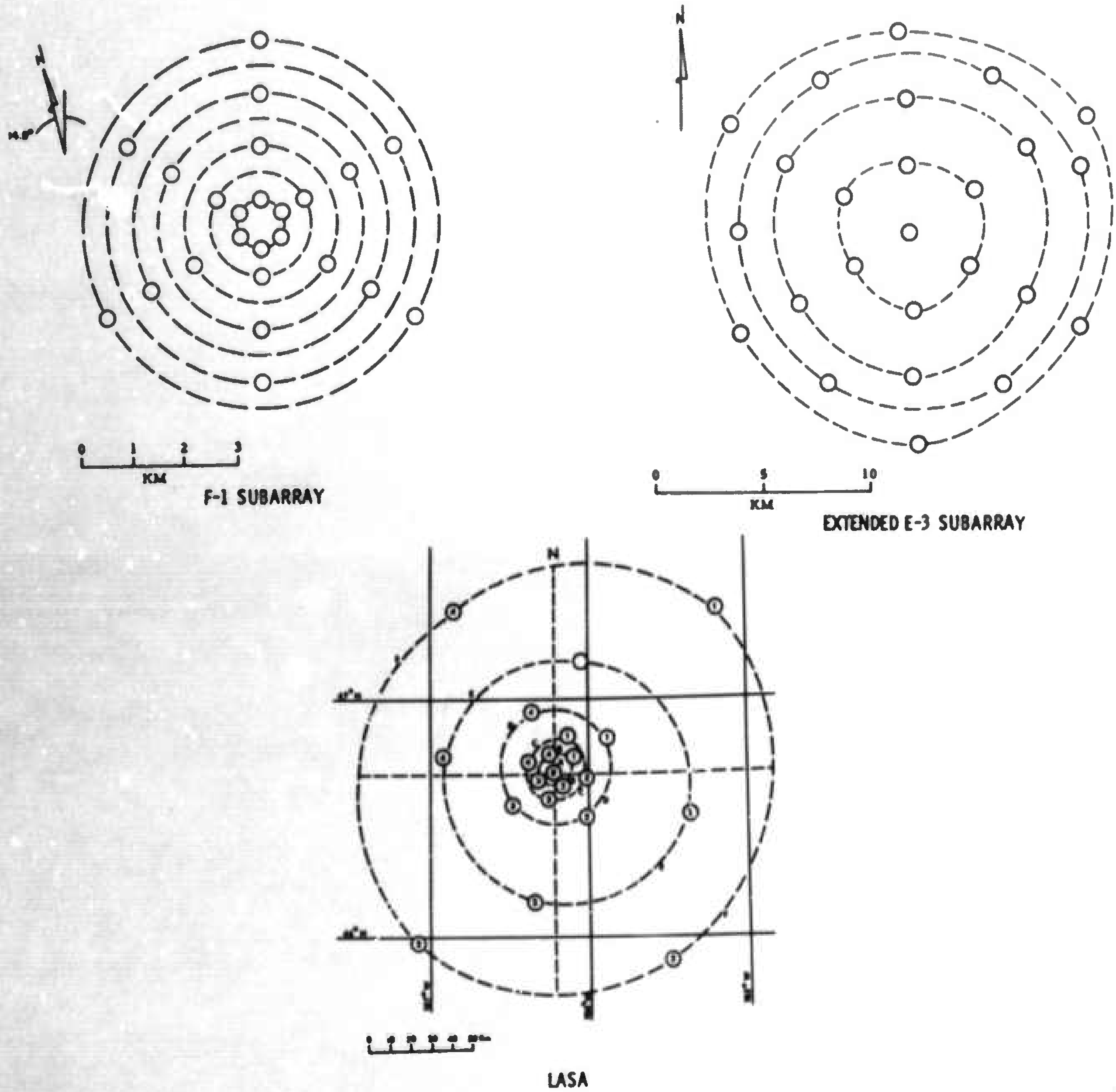

Figure I-1. Array Configurations

A. SHORT-PERIOD EVENTS

Five short-period events of magnitudes ranging from 4.4 to 4.8 were selected to be processed. Table I-1 describes the selected events. Event locations were determined from PDE information supplied by the Coast and Geodetic Survey and the LASA event log. Two of the five events could not be identified; their epicenter locations were estimated from the LASA subarray outputs.

B. ARRAY DESCRIPTION

The largest subarray consisted of outputs from the LASA A0, D-ring subarray. Outer LASA E- and F-rings were not included in frequency-wavenumber analysis because their traveltime anomalies and long moveout times badly disrupt the frequency-wavenumber analysis.[2] The intermediate subarray was composed of the extended E3 subarray, and the smallest subarray was composed of the F1 subarray. In the latter cases, all 25 seismometer outputs were used.

C. EVENT DETECTION

Event location presupposes detection. Event detection was accomplished by digitally simulating the LASA on-line teleseism detector[3] using the subarray sums which had been prefiltered to eliminate the microseism peak and pass the frequency band generally containing most of the P-wave energy.

An independent event detector was connected with each subarray output (sensors were connected with E1, E2, E4, F1, F2, F3, and F4). Single-channel detection consisted of rectifying the channel output and passing the rectified waveform through a low-pass recursive filter of the form

$$A_{n+1} = \alpha (1 - \alpha) A_n + (1 - \alpha) X_n$$

Table I-1

SHORT-PERIOD PDE INFORMATION

Date (1967)	Event No.	Region	Coordinates		Depth (km)	Magnitude	Azimuth (°)	Velocity (km/sec)
			Lat. (°)	Long. (°)				
14 Apr.	1	Northeast China	?	?	?	?	258.5	22.9
8 Mar.	2	Northern Pacific Ocean	25.0N	146.0E	0	4.8	300.0	22.3
5 Mar.	3	Kurile Islands	47.0N	149.0E	0	4.6	313.0	17.5
21 Jun.	4	Mid-Atlantic Ridge	?	?	?	?	115.5	15.8
21 Jun.	5	East Russia, Northeast China	48.0N	127.0E	0	4.4	327.0	19.2

where

$\alpha \quad = e^{-1/300}$

$A_{n+1} \quad$ = filter output at the $n+1^{th}$ point

$X_n \quad = n^{th}$ point of single-channel time series

The most recent rectified time sample, X_n, then was compared with the recursive filter output delayed by 60 sec (i. e., 600 samples). If this ratio is greater than 5.82, the decision is made than an event has occurred; i. e.,

$$X_n / (A_n - 600) > 5.82$$

If four out of the seven (E1, E2, E4, F1, F2, F3, and F4) single-channel detectors indicate that an event is present within a 20-sec interval, the overall decision is that a teleseism has occurred.

The results of applying this detection technique are shown in Figures I-2 through I-6. All 21 subarray outputs are shown after filtering but only the E- and F-ring (less E3) subarray outputs were used in the process.

Individual trace detection intervals are shown as a first point of detection in the trace playbacks. Detection points are indicated by an arrow; however, traces from E and F subarrays which did not trigger a detector are not marked. All five teleseisms were successfully detected using the four-out-of-seven decision rule.

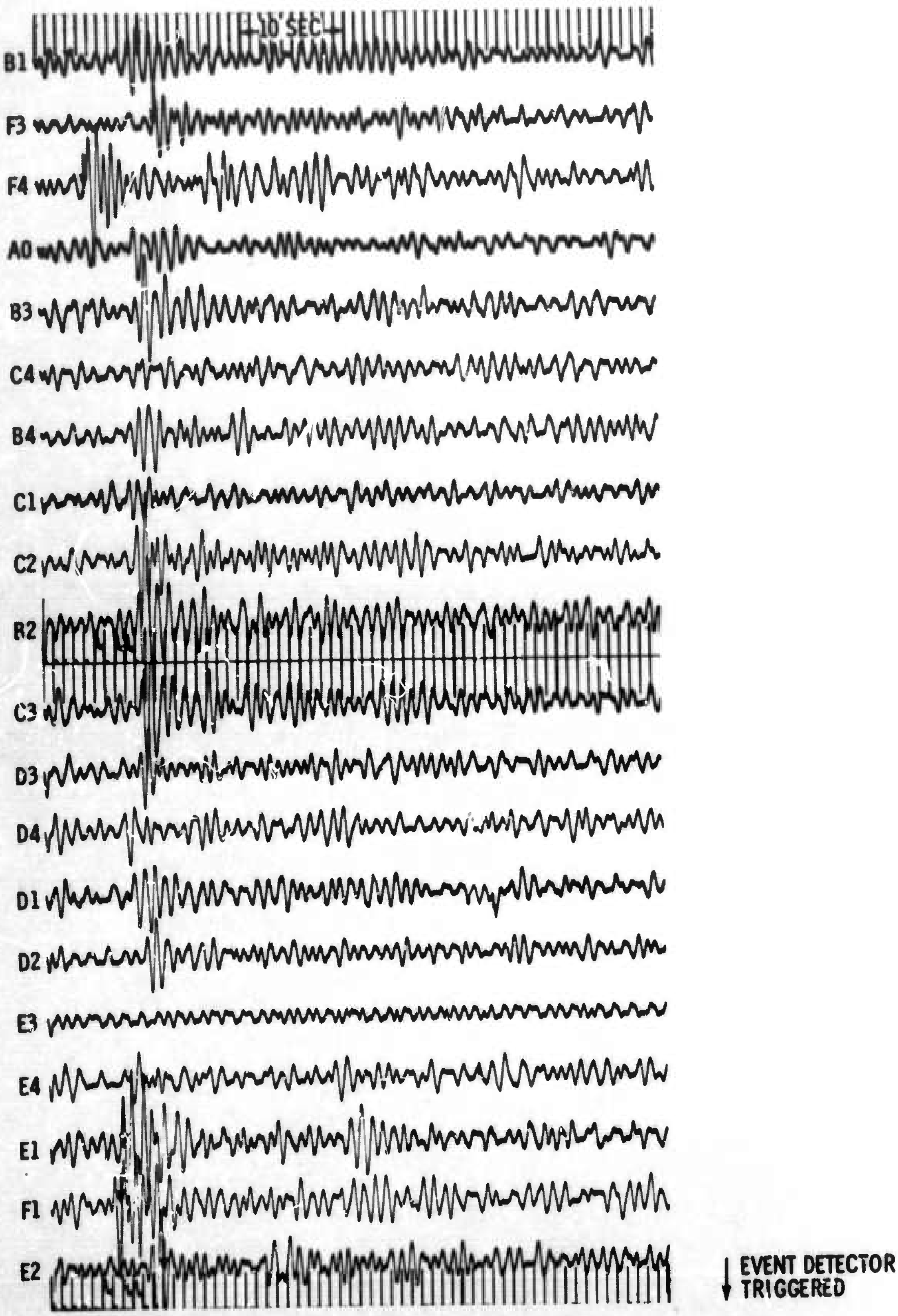

Figure I-2. Filtered Subarray Outputs, Event 1

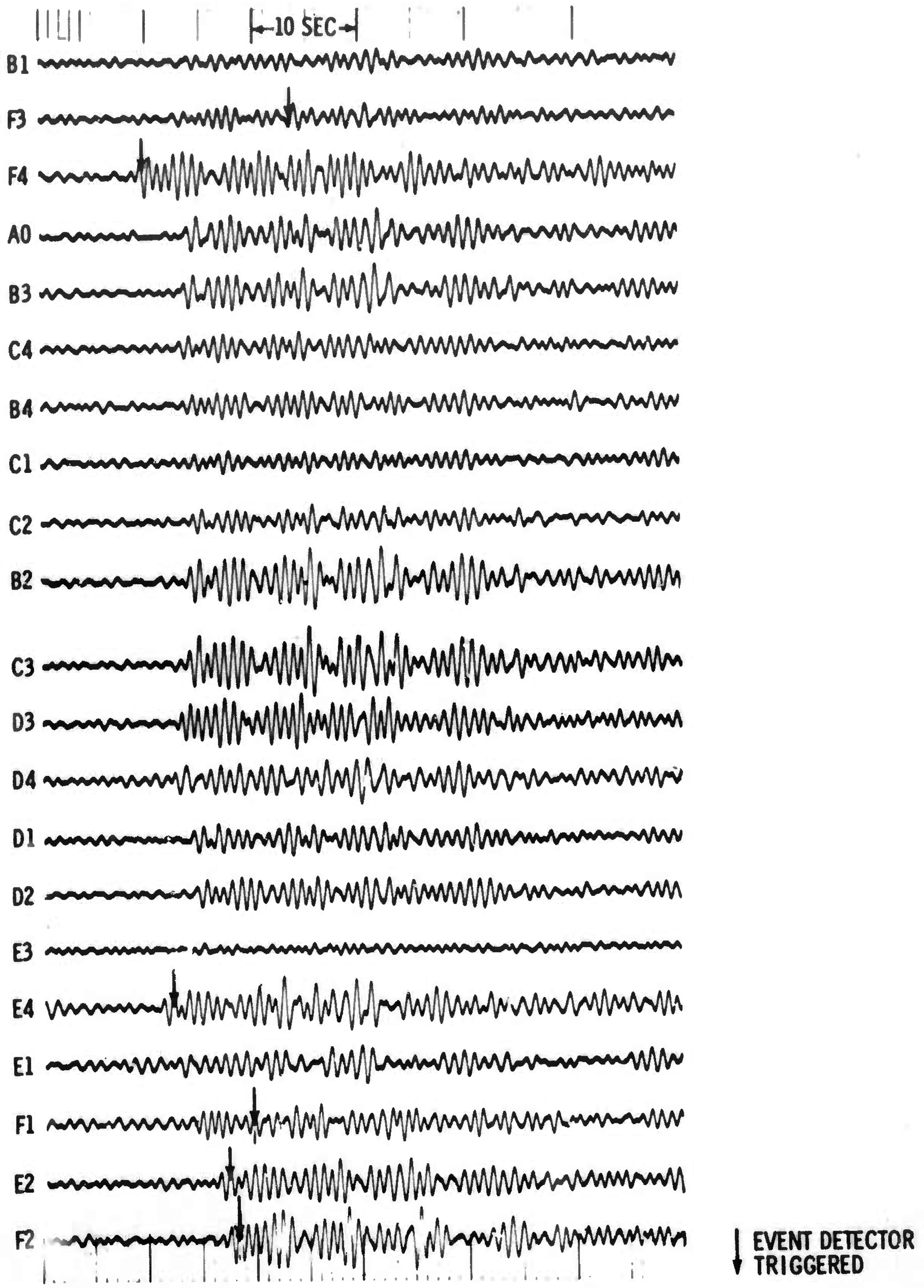

Figure I-3. F-Ring Subarray Outputs, Event 2

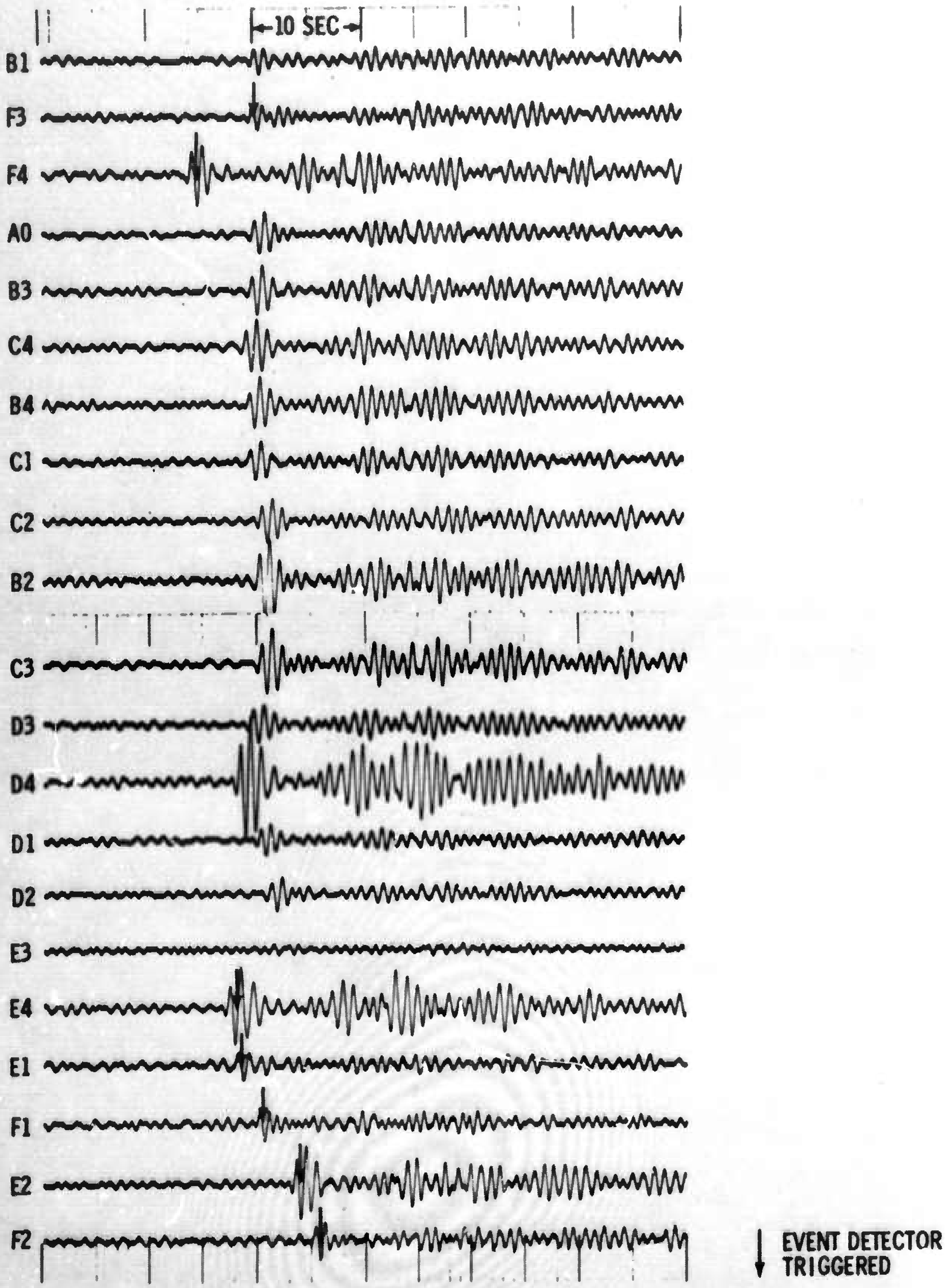

Figure I-4. F-Ring Subarray Outputs, Event 3

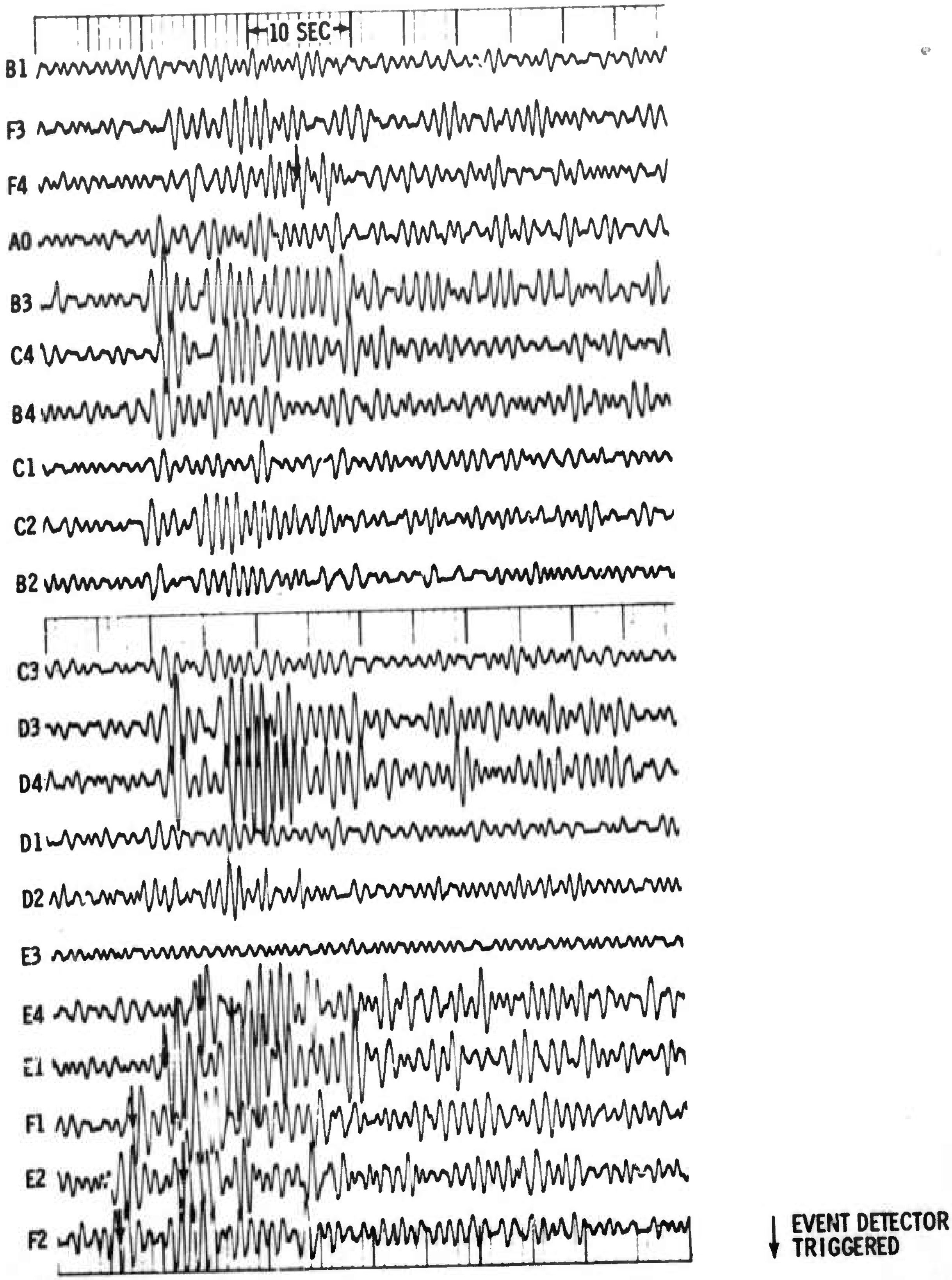

Figure I-5. F-Ring Subarray Outputs, Event 4

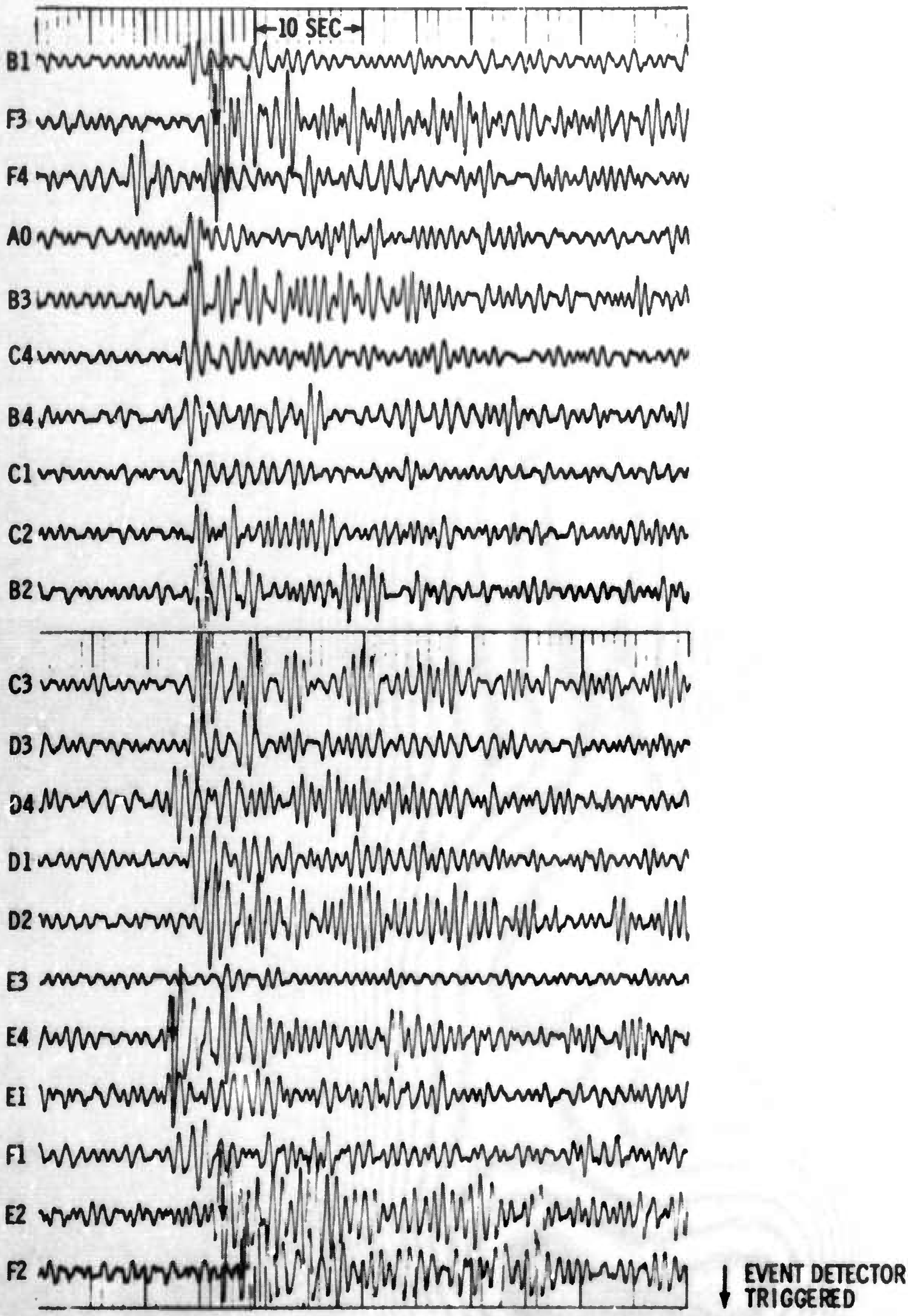

Figure I-6. F-Ring Subarray Outputs, Event 5

SECTION II

MATHEMATICAL DESCRIPTION OF f-$\vec{k}$ SPECTRA

The conventional spectrum is defined as

$$P_1(\vec{V}) = \vec{V}^* \vec{F}\vec{F}^* \vec{V}$$

where

$\vec{V}$ is the vector of phase shifts appropriate for the frequency and velocity of a plane wave propagating across the array

* denotes conjugate transpose

$\vec{F}$ is the vector of Fourier transforms at the desired frequency at each sensor which are taken in the same order as $\vec{V}$

These transforms are taken over a data gate including the P-wave signal and are normalized (only phase information is retained) to remove amplitude anomalies. This may be interpreted as a beamsteer calculated in the frequency domain.

$P_2(\vec{V})$ is defined as

$$\frac{1}{\vec{V}^* \vec{f} \vec{f}^* \vec{V}}$$

where $\vec{f}$ is a vector of filter weights determined by the equation

$$\left[kI + \vec{F}\vec{F}^*\right] |f| = \begin{bmatrix} 0 \\ 0 \\ k \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (2\text{-}1)$$

where

k is a scaler (usually 0.01)

I is the identity matrix

the position of k in the right-hand side of equation 2-1 indicates which channel is used as reference

This process can be thought of as designing a spatial whitening filter and then considering the reciprocal of the power response in wavenumber space of the multichannel filter system.

$P_3(\vec{V})$ is defined as

$$\sum_{i=1}^{k} \frac{1}{\vec{V}^* \vec{f}_i \vec{f}_i^{\,*} \vec{V}}$$

where the $\vec{f}_i$'s are the filter weights designed with the i^{th} sensor used as reference in Equation 2-1. This spectral estimate is obtained using several sensors as reference. If all sensors are used as reference, the result is

$$P_4(\vec{V}) = \frac{1}{V^* (kI + FF^*)^{-2} \vec{V}}$$

$P_5(\vec{V})$ is defined as

$$\frac{1}{\vec{V}^* (kI + \vec{F}\vec{F}^*) \vec{V}}$$

which can be obtained in the following manner. Consider $D = N - M\vec{V}\vec{V}^*$, where N is a measured covariance matrix $(kI + \vec{F}\vec{F}^*)$ and M is a scalar. The problem is to find the largest M such that D will remain a positive definite matrix. D remains a positive definite matrix for

$$M = \frac{1}{\vec{V}^* N^{-1} \vec{V}}$$

This is one measure of how large a portion of the matrix N consists of mode $\vec{V}\vec{V}$. The expression

$$\frac{1}{\vec{V}^* N^{-1} \vec{V}}$$

where $N^{-1} = (kI + \vec{F}\vec{F}^*)^{-1}$, also can be thought of as the output of a maximum-likelihood filter designed to pass the plane-wave signal $|\vec{V}|$ in a noise field having a covariance matrix of $(kI + \vec{F}\vec{F}^*)$.

It should be noted that for the preceding definitions and for using $N = (kI + \vec{F}\vec{F}^*)$, $P_1(\vec{V})$, $P_4(\vec{V})$, and $P_5(\vec{V})$ will necessarily have peaks at the same $\vec{V}$ (Appendix A). Since this study was principally interested in the peaks for location purposes, only estimates of $P_1(\vec{V})$, $P_2(\vec{V})$, and $P_3(\vec{V})$ were computed.

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SECTION III

PROCESSING RESULTS

Five short-period events were processed using a 15-sec gate for the LASA A0, D-ring subarray, a 10-sec gate for the extended E3 subarray, and a 5-sec gate for the F1 subarray. Gate position locations were based on time-trace playbacks and were chosen to include the primary P-wave arrivals.

Plots for all events were made at fixed frequencies of 0.850, 1.000, and 1.115 Hz. An additional plot was made at peak transform frequency computed from the center seismometer time gate.

The subarray outputs used to compute the A0, D-ring f-$\vec{k}$ spectra were a summation of the center element and rings 2, 3, 4, and 5 (13 elements). This configuration was chosen because of good isotropic signal response ($V > 10$ km/sec) and fairly good noise rejection capabilities in the $0.6 \text{ Hz} < f < 1.5 \text{ Hz}$ range.

For the E3 and F1 subarray data, the inputs were the 25 individual sensors. In every case the data was low-cut filtered before taking the transforms.

Results of the frequency-wavenumber processing analysis are summarized in Tables B-1 through B-11 in Appendix B. These tables give the location of the f-$\vec{k}$ spectrum's peak for each type of estimate at each frequency. The tables also contain comments about the behavior of the spectral estimate in the f-$\vec{k}$ region of the incident teleseism. Peak locations and epicenters are specified by dividing the frequency-wavenumber plots into a 3000-point grid numbered from the lower left-hand corner. There are 49 grid

values in the k_x direction and 59 grid values in the k_y direction, with the plot origin at the center of the grid. Consequently, an event arriving with a vertical incidence would be located at $k_x = 25$, $k_y = 30$.

All f-$\vec{k}$ spectra calculated in this experiment are not reproduced in this report. Some spectra from the event recorded on 21 June 1967 from eastern Russia or northeastern China are shown as examples. Figure III-1 shows the three types of f-$\vec{k}$ spectra calculated at 0.85 Hz (the peak power of the center array transform). All f-$\vec{k}$ spectra give a reasonable accurate location at the "peak" frequency for this event; however, this is not true for all events.

Figure III-2 shows the three types of f-$\vec{k}$ spectra calculated at 1.00 Hz. At this frequency none of the f-$\vec{k}$ spectra peak at the proper k, but conventional and high-resolution spectra, using all the outer ring (D-ring) subarrays as reference, did give some indication of the event.

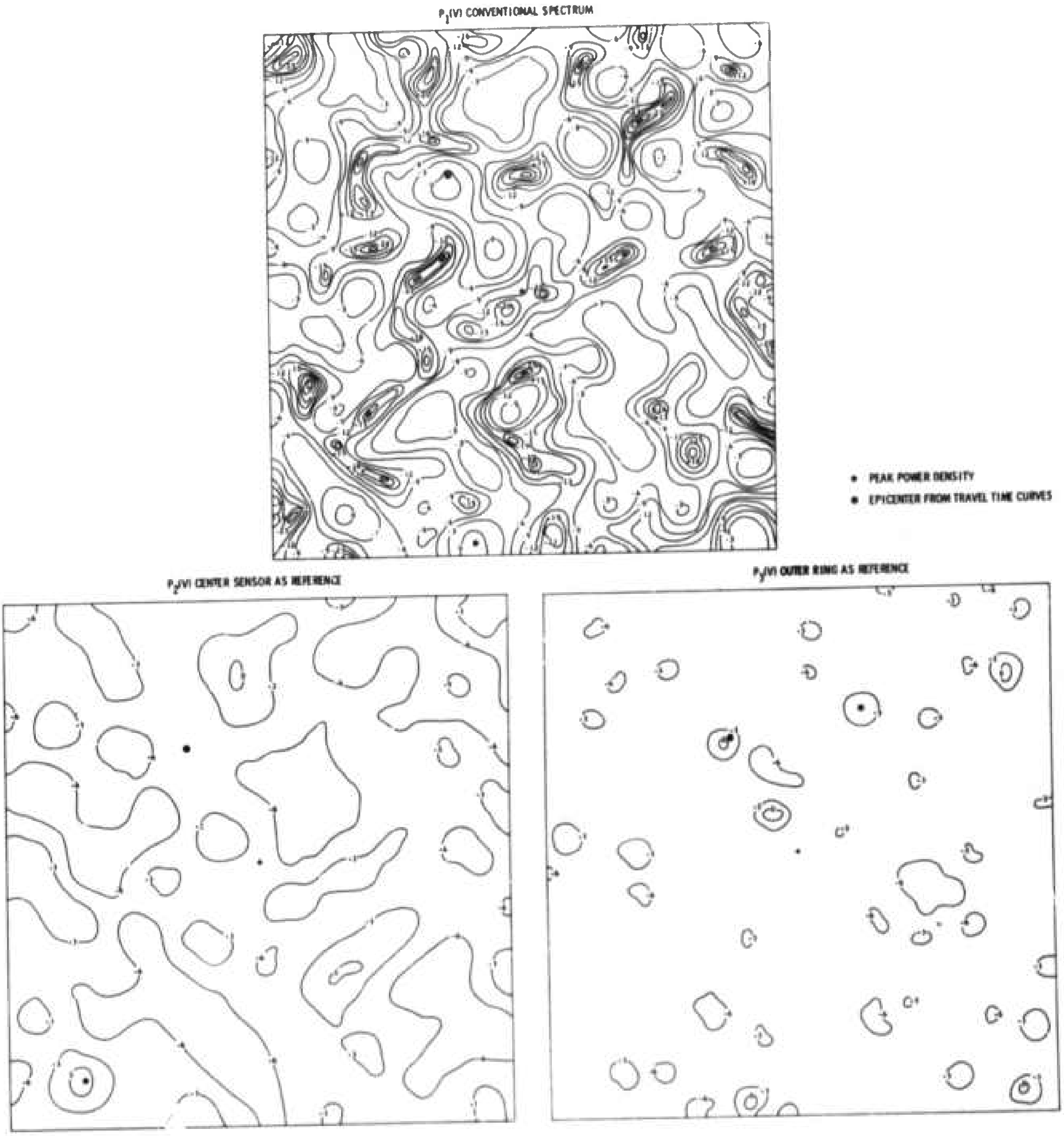

Figure III-1. Frequency-Wavenumber Plots of 21 June 1967 Event at 0.85 Hz

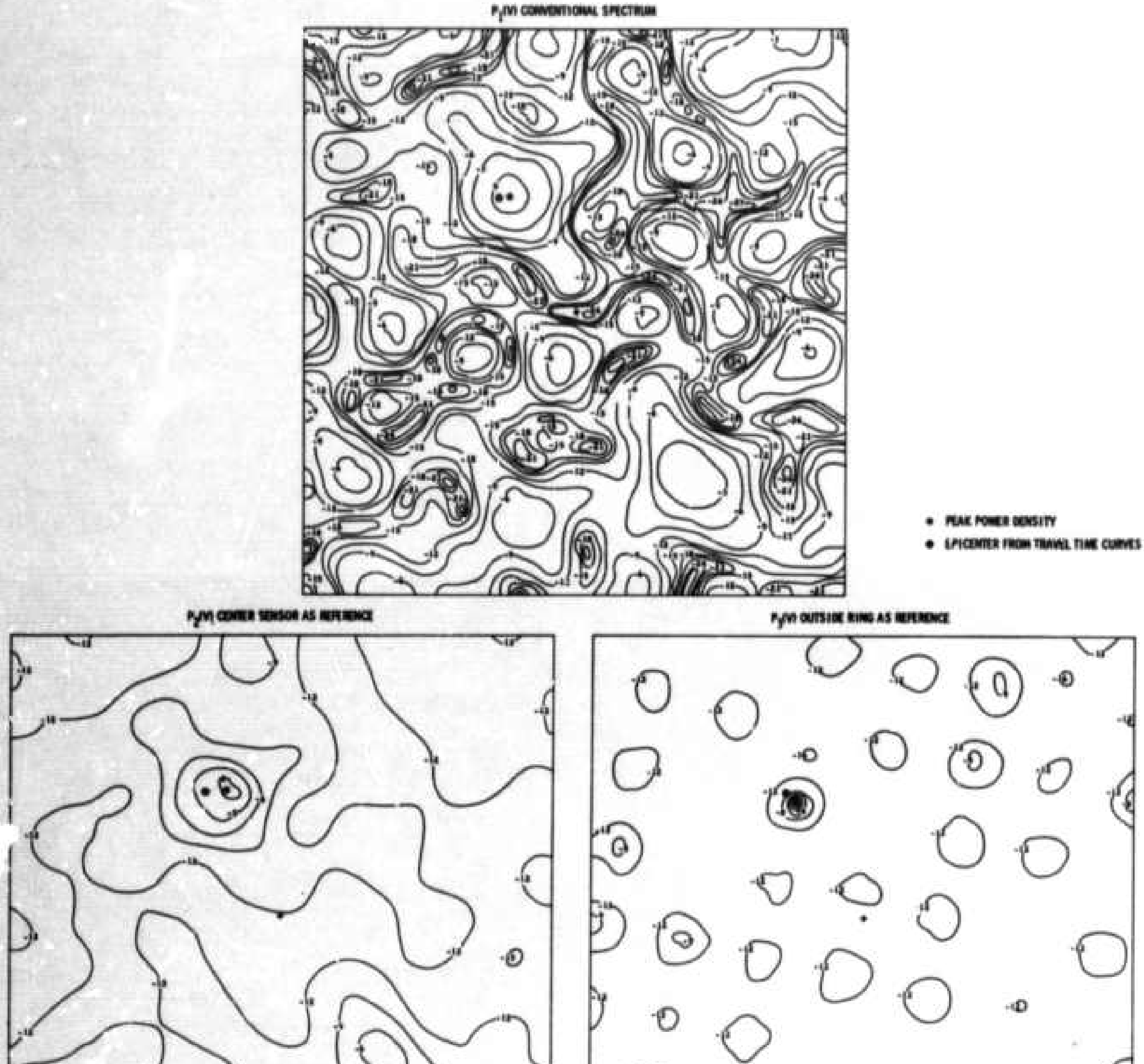

Figure III-2. Frequency-Wavenumber Plots of 21 June 1967 Event at 1.0 Hz

SECTION IV

DISCUSSION OF ON-LINE EVENT LOCATION

This experiment was intended to indicate whether or not $f\text{-}\vec{k}$ spectral techniques offer any advantages for approximate on-line location. Such an on-line location scheme must have a predetermined mode of operation which is either entirely fixed or dependent only upon relatively simple calculations based on incoming data.

Assuming detection, three methods of operation seem reasonable.

- Calculating $f\text{-}\vec{k}$ spectra at a few fixed frequencies which span the band of most energy.
- Calculating peak energy frequency in the signal gate and then calculating an $f\text{-}\vec{k}$ spectrum at this frequency
- Calculating $f\text{-}\vec{k}$ spectra over a range of frequencies and executing a velocity-preserving stack of the resulting spectra

In the third method, this process can be done more efficiently in the time domain for the conventional spectrum as the number of frequencies in the stack increases. In the time domain, this method becomes a bandpass-filter and form-many-beams operation. An $f\text{-}\vec{k}$ approach in this case might be advantageous only if one of the high-resolution techniques proved significantly superior.

The best approximate location at LASA clearly can be obtained using the large array composed of subarray outputs. These outputs have two advantages over individual subarrays: greater aperature and better S/N ratios (on the average). Data using the large array from A0 through the D-ring suggest that $f\text{-}\vec{k}$ epicenter location could be done most reliably by forming velocity-

preserving stacks. The data further indicate that the conventional $P_1(\vec{V})$ spectra are generally more reliable than high-resolution spectra which are the power response of spatial whitening filters $[P_2(\vec{V})$ or $P_3(\vec{V})]$. The implication of these data are that the best strategy for roughly locating events is to use bandpassed data and form beams in the time domain to give a power density picture in the wavenumber or velocity plane.

Data from the extended E3 subarray were limited to three events. In these cases the events could have been located approximately by using either the conventional spectrum at the transform's peak frequency or a velocity preserving stack. These data also indicate that the high-resolution f-$\vec{k}$ spectra $[P_2(\vec{V}) + P_2(\vec{V})]$ generally offer poorer event location than do the conventional spectra $[P_1(\vec{V})]$.

Data from the F1 subarray were limited to three events. In all three cases no reasonable approximate epicenter could be obtained from the F1 subarray data.

SECTION V

REFERENCES

1. Texas Instruments Incorporated, 1968: Location Statistics for f-$\vec{k}$ Processing, Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. 25, Contract AF 33(657)-16678, to be published.

2. Texas Instruments Incorporated, 1967: Traveltime Analysis for LASA, Large-Array Signal and Noise Analysis, Spec. Scientific Rpt. 15, Contract AF 33(657)-16678, 20 Dec.

3. Briscoe, H. W., and P. L. Fush, 1966: "A Real-Time Computing System for LASA", Proceedings, Spring Joint Computer Conference.

APPENDIX A

LOCATION OF MAXIMA FOR $P_1(V)$, $P_4(V)$, and $P_5(V)$

APPENDIX A

LOCATION OF MAXIMA FOR $P_1(V)$, $P_4(V)$, and $P_5(V)$

The following values are given for $P_1(V)$, $P_4(V)$, and $P_5(V)$:

$$P_1(\vec{V}) = \vec{V}^* \vec{F} \vec{F}^* \vec{V} \tag{A-1}$$

$$P_4(\vec{V}) = \frac{1}{\vec{V}^*(kI + \vec{F}\vec{F}^*)^{-2}\vec{V}} \tag{A-2}$$

$$P_5(\vec{V}) = \frac{1}{\vec{V}^*(kI + \vec{F}\vec{F}^*)\,\vec{V}} \tag{A-3}$$

$(kI + FF^*)^{-1}$ and $(kI + FF^*)^{-2}$ may be stated as

$$(kI + \vec{F}\vec{F}^*)^{-1} = \frac{1}{k}\left[I - \frac{\vec{F}\vec{F}^*}{k + \vec{F}^*\vec{F}}\right]$$

$$(kI + \vec{F}\vec{F}^*)^{-2} = \frac{1}{k^2}\left[I - \frac{2k\,\vec{F}\vec{F}^* + \vec{F}\vec{F}^*\vec{F}\vec{F}^*}{(k + \vec{F}^*\vec{F})^2}\right]$$

Substituting these values in Equations A-2 and A-3 yields

$$P_4(\vec{V}) = \frac{k^2}{\vec{V}^*\vec{V} - \dfrac{1}{(k + \vec{F}^*\vec{F})^2}\left[2k\vec{V}^*\vec{F}\vec{F}^*\vec{V} + \vec{V}^*\vec{F}(\vec{F}^*\vec{F})\vec{F}^*\vec{V}\right]} \tag{A-2}$$

$$P_5(\vec{V}) = \frac{k}{\vec{V}^*\vec{V} - \dfrac{1}{k + \vec{F}^*\vec{F}}\left[\vec{V}^*\vec{F}\vec{F}^*\vec{V}\right]} \tag{A-3}$$

Since

$$\vec{V}^*(kI + \vec{F}\vec{F}^*)^{-1}\vec{V} > 0$$

$$\vec{V}^*(kI + \vec{F}\vec{F}^*)^{-2}\vec{V} > 0$$

and

$\vec{V}^*\vec{V}$ = a constant (the number of channels)

$\vec{F}^*\vec{F}$ = a constant (independent of V)

it follows that $P_1(\vec{V})$, $P_4(\vec{V})$, and $P_5(\vec{V})$ will all have a maximum at the maximum of $(\vec{V}^*\vec{F}\vec{F}^*\vec{V})$.

APPENDIX B

SUMMARIES OF FREQUENCY-WAVENUMBER PROCESSING

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Table B-1

14 APRIL 1967 SIGNAL, LASA A0, D-RING

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\bar{k}$ Plot Maximum k_x	f-$\bar{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	70-220	C	23	42	23	41	Multiple peaks on plot, event located on edge, 0+ major peak within -1 db of maximum
1.000		C			45	56	Multiple peaks on plot, event located on edge, 0+ second highest peak within -2 db of maximum
1.150		C			20	11	Multiple peaks on plot, event located on edge of smaller peak within -3 db of maximum
0.900*		C			23	40	Multiple peaks on plot, event located on edge of major peak within -2 db of maximum
0.850		ASR			23	41	Multiple peaks on plot, event located on edge of major peak within -1 db of maximum
0.850		OR			23	40	Many peaks on plot, event located on edge of major peak within -3 db of maximum
1.000		ASR			45	56	Multiple peaks on plot, event located on edge of minor peak within -2 db of maximum
1.000		OR			15	56	Very erratic plot, no significant peak at event location
1.150		ASR			20	11	Multiple peaks on plot, event located on edge of minor peak within -2 db of maximum
1.150		OR			21	12	Erratic plot, many peaks, event located on edge of minor peak within -6 db of maximum
0.900*		ASR			23	40	Multiple peaks on plot, event located on edge of major peak within -6 db of maximum
0.900*		OR			48	57	Erratic plot, many peaks, no peak at event location

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: Stacking would definitely improve the data. Using the outer ring as reference gave much poorer results than using conventional sensors or all sensors as reference with respect to location. Using the outer ring as reference produced a f-$\bar{k}$ plot having more peaks, and the plot maximum had shifted to a poorer location.

Table B-2

8 MARCH 1967 SIGNAL, LASA A0, D-RING

Frequency	Gate	Type Plot**	Location k_x	Location k_y	$f\text{-}\vec{k}$ Plot Maximum k_x	$f\text{-}\vec{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	3730-3880	C	16	37	17	36	Two major peaks on plot, event located on edge, of major peak within -1 db of maximum
1.000*		C			38	50	Two major peaks on plot, event located on edge of minor peak within -1 db of maximum
1.150		C			35	48	Two major peaks, event located on edge of minor peak within -2 db of maximum
1.100		C			36	49	Two major peaks, event located on edge of minor peak within -1 db of maximum
0.850		CS			19	37	Multiple peaks on plot, event located on edge of major peak within -1 db of maximum
0.850		OR			43	54	Erratic plot, many peaks, event located on edge of peak within -3 db of maximum
1.000*		CS			47	22	Many peaks on plot, event located on edge of peak within -4 db of maximum
1.000*		OR			39	51	One major peak on plot, event located on edge of minor peak, within -7 db of maximum
1.150		CS			6	59	Two major peaks on plot, event not indicated
1.150		OR			39	35	Erratic plot, many peaks, event located near a strong peak
1.100		CS			48	26	Three major peaks, event not indicated
1.100		OR			36	49	Many peaks, event located near minor peak

* Denotes maximum

** C = Conventional, $P_1(V)$
ASP = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: The data would be improved by stacking. Relative peaks line up. Conventional $f\text{-}\vec{k}$ spectra gave best results. Using the outer ring as reference produced many more peaks than appeared on conventional spectra.

Table B-3

5 MARCH 1967 SIGNAL, LASA A0, D-RING

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\bar{k}$ Plot Maximum k_x	f-$\bar{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	4085-4235	C	15	41	16	41	Three major peaks on plot. Event on edge of highest peak within -1 db of maximum
1.000		C			16	41	Three major peaks on plot. Event on edge of highest peak within -1 db of maximum
1.150		C			16	40	Three major peaks on plot. Event within -1 db of maximum and on edge of highest peak
1.050*		C			16	41	Four major peaks on plot. Event within -1 db of maximum and on edge of highest peak
0.850		CS			18	43	One major peak on plot, many minor peaks. Event on far edge of major peak within -3 db of maximum
0.850		OR			16	41	Very many major peaks on plot, event located on edge of highest peak within -2 db of maximum
1.000		CS			16	41	One major peak on plot, very sharp peak. Event located on edge of peak, within -4 db of maximum
1.000		OR			16	40	Very many peaks on plot, event located on edge of major peak within -1 db of maximum
1.150		CS			17	41	One major peak on plot, event located on edge of major peak within -1 db of maximum
1.150		OR			16	40	Very many peaks on plot, event located on edge of highest peak within -4 db of maximum
1.050*		CS			17	42	One major peak on plot, event located on edge of major peak within -4 db of maximum
1.050		OR			16	40	Many major peaks on plot, event located on edge of highest peak within -4 db of maximum

* Denotes Maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

***Relative to plot maximum

Comments: Conventional spectra would be greatly improved by stacking. The major peak is stationary and would add while the minor peaks move about as a function of frequency. In no case did high-resolution spectrum do a better job of location than the conventional and in some cases they were slightly worse. The high-resolution spectra would be improved by stacking. The spectra gave a good, consistent event location.

Table B-4

21 JUNE 1967 SIGNAL, LASA A0, D-RING

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\vec{k}$ Plot Maximum k_x	f-$\vec{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850*	790-940	C	40	22	40	22	Three major peaks on plot, event located on edge of major peak within -1 db of plot maximum
1.000		C			42	19	Four major peaks on plot, event located on edge of major peak within -1 db of maximum
1.150		C			14	35	Five major peaks on plot, event located on edge of minor peak within -3 db of plot maximum
0.750		C			40	23	Two major peaks on plot, event located on edge of minor peak within -1 db of plot maximum
0.850*		CS			24	53	Two major peaks on plot, event located on edge of minor peak within -1 db of plot maximum
0.850*		OR			9	22	Many peaks on plot, event located on edge of minor peak, within -2 db of plot maximum
1.000		CS			1	25	Three major peaks on plot, event located off edge of minor peak within -6 db of plot maximum
1.000		OR			30	39	Very many peaks on plot, event located on minor peak within -3 db of plot maximum
1.150		CS			14	35	One major peak on plot, no indication of event
1.150		OR			6	25	Two major peaks on plot, no indication of event
0.750		CS			40	23	One major peak on plot, event located on edge of major peak within -1 db of plot maximum
0.750		OR			39	24	One sharp peak on plot, event located off edge of peak within -7 db of plot maximum

* Denotes Maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: The data would be improved by stacking. As a whole, the conventional spectra gave much better proper event location. The high-resolution spectra, except at the peak frequency, moved the plot maximum around a good bit.

Table B-5

21 JUNE 1967 SIGNAL, LASA A0, D-RING

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\vec{k}$ Plot Maximum k_x	f-$\vec{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850*	2235-2385	C	18	43	19	42	Three major peaks on plot, event located on edge of major peak within -1 db of plot maximum
1.000		C			20	2	Very many major peaks on plot, event located on peak within -1 db of plot maximum
1.150		C			19	42	Many peaks on plot, event located on edge of major peak within -1 db of plot maximum
0.700		C			19	8	Three major peaks on plot, event located on edge of major peak within -1 db of maximum
0.850*		CS			20	43	One major peak on plot, event located on edge of major peak within -3 db of maximum
0.850*		OR			19	42	One sharp peak on plot, event located off edge of peak within -10 db of plot maximum
1.000		CS			8	6	Many major peaks on plot, no indication of event
1.000		OR			31	46	Many peaks on plot, event located on edge of peak within -2 db of plot maximum
1.150		CS			19	41	Three major peaks on plot, event located on edge of highest peak within -2 db of maximum
1.150		OR			5	33	One large peak on plot, event located on small peak within -6 db of plot maximum
0.700		CS			17	41	Two major peaks on plot, event located on edge of largest peak within -2 db of plot maximum
0.700		OR			21	37	Many peaks on plot, event does not fall on peak

* Denotes Maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: Stacking would improve the data. Conventional spectra gave the best event location. High-resolution spectra using the outer-ring as reference sometimes gave a sharper peak, but the location was poorer.

Table B-6

21 JUNE 1967 SIGNAL, EXTENDED E3 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\vec{k}$ Plot Maximum k_x	f-$\vec{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	70-170	C	23	42	1	28	Two major peaks on plot, event located on edge of lower peak within -3 db of plot maximum
1.000		C			21	40	Single major peak on plot, event located within -1 db of maximum
1.150		C			25	41	Two major peaks on plot, event located on edge of higher peak within -2 db of maximum
0.950*		C			21	40	Three major peaks on plot event located on edge of highest peak within -1 db of maximum
0.850		ASR			1	28	Two flat peaks on plot event located within -1 db of plot maximum; all magnitudes within -2 db of maximum
0.850		OR			4	33	Multiple peaks on plot event located on edge of one of the peaks within -2 db of maximum
1.000		ASR			21	40	Two peaks on plot, event located on edge of higher peak within -1 db of maximum
1.000		OR			25	39	One major peak on plot, event located on edge of major peak within -5 db of plot maximum
1.150		ASR			25	41	Two flat peaks on plot, event located on edge of major peak, all magnitudes within -2 db of maximum
1.150		OR			26	41	Multiple peaks on plot, event located on edge of major peak within -1 db of maximum
0.950*		ASR			21	40	Three flat peaks on plot, event located on edge of major peak within -1 db of maximum
0.950*		OR			5	28	Multiple peaks on plot, event located on edge of one of the higher peaks within -2 db of maximum

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: The spectral plots using the outer-ring as reference have a much sharper peak; however, event location is poorer. The data would be improved by stacking in that the relative peaks would add.

Table B-7

21 JUNE 1967 SIGNAL, EXTENDED E3 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\bar{k}$ Plot Maximum k_x	f-$\bar{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	780-880	C	40	22	40	22	One major peak on plot, event located at maximum of major peak
1.000		C			39	24	One major peak on plot, event located on edge of major peak within -1 db of maximum
1.150		C			37	28	One major peak on plot, event located on edge of major peak within -2 db of plot maximum
0.950*		C			39	21	One major peak on plot, event located on edge of peak within -1 db of plot maximum
0.850		CS			37	19	One major peak on plot, event located on edge of major peak within -1 db of plot maximum
0.850		OR			42	21	One sharp peak on plot, event located on edge of peak within -3 db of plot maximum
1.000		CS			39	23	One major peak on plot, event located on edge of peak within -1 db of plot maximum
1.000		OR			40	24	One sharp peak on plot, event located on edge of peak within -2 db of maximum
1.150		CS			34	33	Four major peaks on plot, event located between two peaks
1.150		OR			32	33	Many major peaks on plot, event not located at peak
0.950*		CS			40	20	One major peak on plot, event located on edge of peak within -1 db of maximum
0.950*		OR			43	18	One sharp peak on plot, event located off edge of peak within -7 db of maximum

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: These plots would be improved by stacking. The conventional spectra did as well or better than the high-resolution spectra in event location. The high-resolution spectra, using the outer ring as reference, gave sharper peaks in f-$\bar{k}$ space, but the event location was poorer.

Table B-8

21 JUNE 1967 SIGNAL, EXTENDED E3 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-$\vec{k}$ Plot Maximum k_x	f-$\vec{k}$ Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	2250-2350	C	18	43	19	43	One major peak on plot, event located on edge of peak within -1 db of plot maximum
1.000		C			20	43	One major peak on plot, event located on edge of peak within -1 db of plot maximum
1.150*		C			18	40	One major peak on plot, event located on edge of peak within -1 db of plot maximum
1.200		C			16	39	One major peak on plot, event located on edge of peak within -2 db of plot maximum
0.850		CS			20	36	One major peak on plot, event located on edge of peak within -2 db of plot maximum
0.850		OR			19	51	One flat peak on plot, all magnitudes within -3 db of maximum
1.000		CS			20	41	One major peak on plot, event located on edge of peak within -1 db of maximum
1.000		OR			18	44	One major peak on plot, event located on edge of peak within -1 db of maximum
1.150*		CS			18	40	One major peak on plot, event located on edge of peak within -4 db of plot maximum
1.150*		OR			13	39	One sharp peak on plot, event located off edge of peak within -19 db of plot maximum
1.200		CS			17	41	One major peak on plot, event located on edge of peak within -2 db of plot maximum
1.200		OR			18	34	One major peak on plot, event not indicated

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: The data would be improved by stacking. Conventional spectra did better at particular frequencies while high-resolution did better at others.

Table B-9

14 APRIL 1967 SIGNAL, STANDARD F1 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	$\vec{f}$-k Plot Maximum k_x	$\vec{f}$-k Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	60-110	C	23	42	35	49	Single peak on plot, event located within -1 db of peak
1.000		C			30	44	Single peak on plot, event located within -1 db of peak
1.150		C			23	41	Single peak on plot, event located within -1 db of peak
0.950*		C			31	45	Single peak on plot, event located within -1 db of peak
0.850		ASR			35	49	Single peak on plot, event located within -4 db of peak
0.850		OR			36	54	Single peak on plot, event located within -13 db of peak
1.000		ASR			30	44	Single peak on plot, event located within -3 db of peak
1.000		OR			29	52	Single peak on plot, event located within -16 db of peak
1.150		ASR			23	41	Single peak on plot, event located within -1 db of peak
1.150		OR			12	50	Single peak on plot, event located within -7 db of peak
0.950*		ASR			31	45	Single peak on plot, event located within -2 db of peak
0.950*		OR			31	52	Single peak on plot, event located within -17 db of peak

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: Using the outer ring as reference gave a much sharper peak in f-k space contrasted to using all sensors as reference. The -3 db contour, relative to the plot maximum, was 5 to 6 times more narrow than the all-sensors-as-reference -3 db contour. However, the location was poorer in all cases. No improvement would result from stacking the data.

Table B-10

21 JUNE 1967 SIGNAL, STANDARD F1 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	$\vec{f}$-k Plot Maximum k_x	$\vec{f}$-k Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	765-815	C	40	22	38	33	One broad major peak on these plots
1.000		C			39	34	All plots were flat within -9 db
1.150		C			38	35	The event was consistently located on the lower edge
0.900*		C			39	33	Within -1 db peak of maximum
0.850		CS			30	37	Broad single peaks on all these plots
0.850		OR			40	37	All plots were flat within 17 db
1.000		CS			34	34	Event location was poorer than conventional spectra
1.150		CS			35	39	
1.150		OR			27	35	
0.900*		CS			32	36	
0.900*		OR			45	40	

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: The conventional and high-resolution spectra gave consistently wrong event location. Stacking would reinforce this erroneous location

Table B-11

21 JUNE 1967 SIGNAL, STANDARD F1 SUBARRAY

Frequency	Gate	Type Plot**	Location k_x	Location k_y	f-k Plot Maximum k_x	f-k Plot Maximum k_y	Event Relative Maximum*** (db, k_x, k_y)
0.850	2260-2310	C	18	43	5	45	One broad peak on plots, stacking would not improve location since all plots are poor as to event location, event within -2 db of plot maximum
1.000		C			10	38	
1.150		C			17	48	
0.900*		C			8	42	
0.850		CS			1	42	One peak on all plots, plot maximum varies as a function of frequency and choice of reference sensors, stacking would not give much improvement in event location since all plots had a poor event location (as to plot maximum)
0.850		OR			11	50	
1.000		CS			1	40	
1.000		OR			15	46	
1.150		CS			16	46	
1.150		OR			10	43	
0.900*		CS			1	42	
0.900*		OR			12	48	

* Denotes maximum

** C = Conventional, $P_1(V)$
ASR = All sensors reference, $P_4(V)$
CS = Center sensor reference, $P_2(V)$
OR = Outer ring reference, $P_3(V)$

*** Relative to plot maximum

Comments: Both conventional and high-resolution spectra gave poor results as to placing plot maximum at event location.

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13. ABSTRACT

Five short-period events were processed using a 15-sec gate for the LASA A0, D-ring subarray, a 10-sec gate for the extended E3 subarray, and a 5-sec gate for the F1 subarray. Gate positions were based on time-trace playbacks and were chosen to include the primary P-wave arrivals.

For an event recorded on 21 June 1967 from eastern Russia or northeastern China, all f-k give a reasonable accurate location at the "peak" frequency for this event; however, this is not true for all events. Three types of f-k spectra were calculated at 1.00 Hz. At this frequency none of the f-k spectra peak at the proper k, but conventional and high-resolution spectra, using all the outer ring (D-ring) subarrays as reference, did give some indication of the event. ( )

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